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Performance and operation of a rotating biological contactor in a tilapia recirculating aquaculture system

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Abstract

This paper describes the performance characteristics of an industrial-scale air-driven rotating biological contactor (RBC) installed in a recirculating aquaculture system (RAS) rearing tilapia at 28 °C. This three-staged RBC system was configured with stages 1 and 2 possessing approximately the same total surface area and stage 3 having approximately 25% smaller. The total surface area provided by the RBC equaled 13,380 m^2. Ammonia removal efficiency averaged 31.5% per pass for all systems examined, which equated to an average ($\pm$ standard deviation) total ammonia nitrogen (TAN) areal removal rate of 0.43 ± 0.16 g/m^2/day. First-order ammonia removal rate (K_1) constants for stages 1–3 were 2.4, 1.5, and 3.0 h^{-1}, respectively. The nitrite first-order rate constants (K_2) were higher, averaging 16.2 h^{-1} for stage 1, 7.7 h^{-1} for stage 2, and 9.0 h^{-1} stage 3. Dissolved organic carbon (DOC) levels decreased an averaged 6.6% per pass across the RBC. Concurrently, increasing influent DOC concentrations decreased ammonia removal efficiency. With respect to dissolved gas conditioning, the RBC system reduced carbon dioxide concentrations approximately 39% as the water flowed through the vessel. The cumulative feed burden – describes the mass of food delivered to the system per unit volume of freshwater added to the system daily – ranged between 5.5 and 7.3 kg feed/m^3 of freshwater; however, there was no detectable relationship between the feed loading rate and ammonia oxidation performance.
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Keywords: Biofiltration; Rotating biological contactor; Aquaculture; Recirculating aquaculture system; Nitrification

1. Introduction

Water quality maintenance in recirculating aquaculture systems (RAS) is focused on the detoxification of nitrogenous wastes, oxygenation, removal of suspended solids, and controlling the accumulation of organic compounds. Once the system's oxygen requirement, which includes that needed for fish respiration and microbial processes, is met, nitrogenous wastes, primarily ammonia, become the next important limiting factors (Lawson, 1995). Ammonia accumulation in recirculating systems is controlled through water exchange and biofiltration. Through biofiltration, ammonia is oxidized to nitrate during the nitrification process, which requires oxygen and alkalinity. Carbon dioxide (CO_2) is another water quality parameter that can be reach problematic

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concentrations in intensively (high stocking densities) managed RAS systems. Carbon dioxide is control through aggressive aeration of the water either by surface agitation or by passing the culture water through aeration columns (Summerfelt et al., 2000).

Biofilter configurations are broadly categorized as either submerged (e.g. fluidized bed, bead filters) or emerged (rotating biological contactor/biodrum, trickling filter) filters. In submerged filters, the media remains below the water surface, where as in emerged filters, the media is alternately exposed or continuously to ammonia-laden water and the atmosphere. Several studies have described the performance of fluidized bed filters (Sandu et al., 2002; Summerfelt and Sharrer, 2004), trickling filters (Kamstra et al., 1998), and microbead filters (Greiner and Timmons, 1998) from large production scale systems but there has been little information on the performance of rotating biological contactor (RBC) systems in commercial aquaculture operations.

This paper characterizes the performance of an industrial-scale RBC installed in recirculating aquaculture system modules culturing tilapia at Blue Ridge Aquaculture (Martinsville, VA, production exceeded 1380 metric tonnes at the time of these studies). Additionally, the operational characteristics of the RBC are compared to the predominant aquaculture biofilter configurations that include the bead, fluidized bed, micro-bead, and trickling filters.

2. Rotating biological contactors

The term RBC generally defines a class of the fixed film biologic filters where the media is attached to a central horizontal shaft that is rotated to temporarily submerge a portion of the media in the water. The concept was first developed in 1900 for biologically treating domestic wastewater (Hynek and Chou, 1979). However, commercial development, research, and installation were not seen until the 1970s in Germany and the United States (Wheaton et al., 1994b). During this time, the development of media with high specific surface area increased removal rates and helped reduce costs (Hynek and Chou, 1979). RBCs (Fig. 1) are typically constructed of plastic media disks or molded sections that are closely spaced to provide a relatively large total surface area within a relatively small space, but far enough apart so that the filter does not clog from biological growth and bridging. Excess biofilm growth is mechanically sheared as the media surface rotates through the water. RBC shafts can be positioned parallel or perpendicular to the water flow. Rotation of the shaft can be controlled by a shaft drive motor (Ayoub and Saikaly, 2004), an airlift system (Hynek and Chou, 1979), or water jet (Van Gorder and Jug-Dujakovic, 2004).

2.1. Factors affecting ammonia oxidation performance

2.1.1. Mass and hydraulic loading

Generally, aquaculture-based nitrification systems operate at ammonia concentrations less than 3–5 mg/L, which limits mass transport rates of ammonia into the biofilm (Rittman and McCarty, 1980). Wheaton et al. (1994a) citing Hochheimer (1990) and Brune and Gunter (1981) argued that in the ammonia limited conditions of the aquaculture environments, the mass loading rate (Λ_{M_x}, g/(m^2 day)) of ammonia regulated nitrifier growth rate and the nitrification rate, not the ammonia concentration. The mass loading rate is calculated as:

$$\Lambda_{M_x} = \left[\frac{\frac{QS_o}{A_{TS}}}{1000\,(\mathrm{mg/g})} \right] \tag{1}$$

Here, Q defines the mass daily flow (m^3/day) of water across the filter, S_o defines the influent substrate concentration (mg/L $\times$ 1000 L/m^3), and A_{TS} is the total filter surface area (m^2), not just the wetted portion. Mass removal rate (R_{M_x}, g/(m^2 day)) is calculated as:

$$R_{M_x} = \left[\frac{\frac{Q[S_o - S_E]}{A_{TS}}}{1000\,(\mathrm{mg/g})} \right] \tag{2}$$

where S_E is effluent substrate (mg/L $\times$ 1000 L/m^3).

Hydraulic loading also affects the ammonia removal rate. Increasing the flow rate through the biofilter decreases the water detention time within the biofilter vessel and results in a reduction in the single pass removal efficiency (Kaiser and Wheaton, 1983). However, the increased flow rate can result in higher mass ammonia removal than at lower flow rates, which facilitate higher removal efficiencies per pass (Drapcho and Brune, 1984; Easter, 1992).

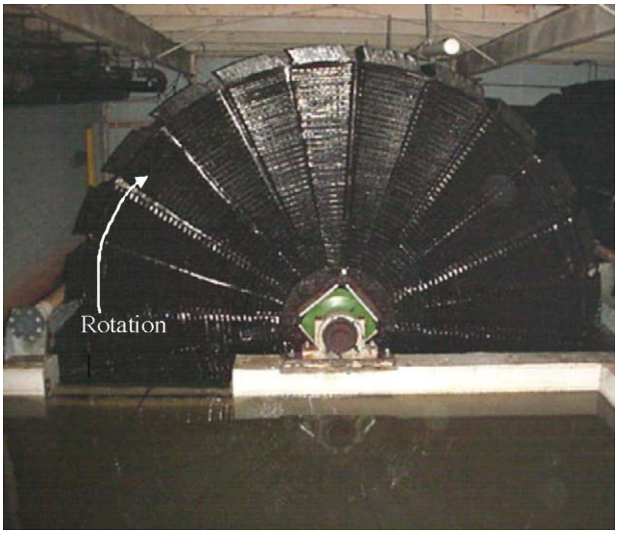

Fig. 1. Image of the model 769-253-HHH RBC system (Envirex Inc., US Filter) installed in the recirculating aquaculture system being evaluated.

Because of the interaction between hydraulic loading and mass loading on removal performance, care must be taken not to use the terms interchangeably. The hydraulic (Λ_H, m/day [$m^3/(m^2\,day)$]) loading rate defines the water flow rate (Q, m^3/day) across the biofilter per unit of total surface area (A_{TS}, m^2, Grady et al., 1999) and is calculated as:

$$\Lambda_H = \frac{Q}{A_{TS}} \tag{3}$$

For a constant influent substrate concentration, an increase in hydraulic loading results in a proportional increase in the mass of substrate delivered to the filter (Wu et al., 1981; Rogers and Klemetson, 1985). Thus, an increase in mass loading does not implicitly indicate a change in water flow.

In RAS applications, the hydraulic loading is often determined as a function ammonia concentration desired in the culture tank and the required mass removal rate to achieve that level. Consequently, high water recirculation rates are used to minimize the effect of the relatively low concentrations and achieve sufficient removal rates with relatively small sized biofilter systems (Easter, 1992). Hochheimer and Wheaton (1998) recommended a maximum hydraulic loading design limit for RBCs of 300 $m^3/(m^2\,day)$ based on criteria described in Grady and Lim (1980).

2.1.2. Rotational speed

RBC rotational velocities (ω) range typically from 0.18 to 0.35 m/s for both aquaculture and domestic wastewater installations (Friedman et al., 1979; Miller and Libey, 1985; Gilbert et al., 1986; Easter, 1992; Ayoub and Saikaly, 2004; Van Gorder and Jug-Dujakovic, 2004). In a lab-scale RBC unit treating synthetic waste stream, ammonia removal performance increased with increasing disk rotational speed (Odal et al., 1981). Friedman et al. (1979) observed a similar trend in organic removal while demonstrating the limits of this effect. For any specific loading, increases the disc rotational speed improved the removal efficiency but eventually, the removal efficiency remained constant even though rotational speed was increased.

2.1.3. Organic loading

Nitrification is significantly influenced by the organic loading (WEF, 1992). Biodegradable soluble organic compounds (SOC) provide a substrate that aerobic heterotrophic bacteria utilize for growth (Hagopian and Riley, 1998). Heterotrophs have been reported to grow at rates five times faster than nitrifiers, which utilize inorganic carbon sources as electron donors (Grady and Lim, 1980). This electron transfer is a low energy-yielding pathway and results in slow growth. This allows heterotrophic populations to expand within the biofilter and displace nitrifying bacteria (Hagopian and Riley, 1998). Thus, as the influent SOC concentration increases, heterotrophic populations increase, which decreases nitrification performance until the SOC becomes limiting with respect to heterotrophic bacteria. At this point, nitrifying bacteria populations can expand. SOCs are grossly measured as 5-day biological oxygen demand (BOD_5) or chemical oxygen demand (COD) and occasionally, dissolved organic carbon (DOC) (Metcalf and Eddy Inc., 1991). Zhu and Chen (2001) reported that ammonia oxidation was reduced by 70% when influent carbon to nitrogen (C/N) ratio of 1, which was equivalent at a BOD_5/TAN ratio of 1.76.

2.1.4. Staging

One means of improving removal performance is to compartmentalize or stage the RBC. Here, RBC media sections are positioned over individual basins that are positioned in series (Metcalf and Eddy Inc., 1991). Grady and Lim (1980) reported that a single stage RBC performs similarly to a completely stirred tank reactor (CSTR) and that multiple stages can be modeled as a series of CSTRs, which begin to achieve removal characteristics similar to that of a plug flow reactor. The authors indicated that multiple smaller units in series achieve greater constituent reduction than a single unit of the same total media and hydraulic volume. This serial configure facilitates bacterial population segregation as they acclimate to the different conditions within the treatment basin. This results in separate stage carbon reduction and nitrification (Weng and Molof, 1974; Hiras et al., 2004). For example, in a three-staged RBC treating a waste stream possessing SOCs and ammonia, heterotrophs would dominate the first stage, while nitrification would be measured in the latter stages.

3. Methods and materials

3.1. Commercial-scale RAS configuration and operation

Nine RBC units, each operating on an independent recirculating aquaculture system, were studied during this evaluation. Water exiting the culture tank (215 m^3) flowed through a 37 m^3 multi-tube clarifier basin and was then directed through the industrial-scale RBC unit (Model 769-253-HHH, US Filter/Envirex Corporation, Waukesha, WI, Fig. 1). The treated water was then pumped (3.8 m^3/min) down a U-tube oxygenation system before reentering the culture tank.

Each RBC unit was constructed with three stages, and positioned with the central axis parallel to the treatment flow (Fig. 2B). The first two stages were equally sized (3.7 m diameter × 2.7 m long), providing 4880 m^2 of surface area each and the third stage, which was shorter (2.2 m) provided 3620 m^2 of

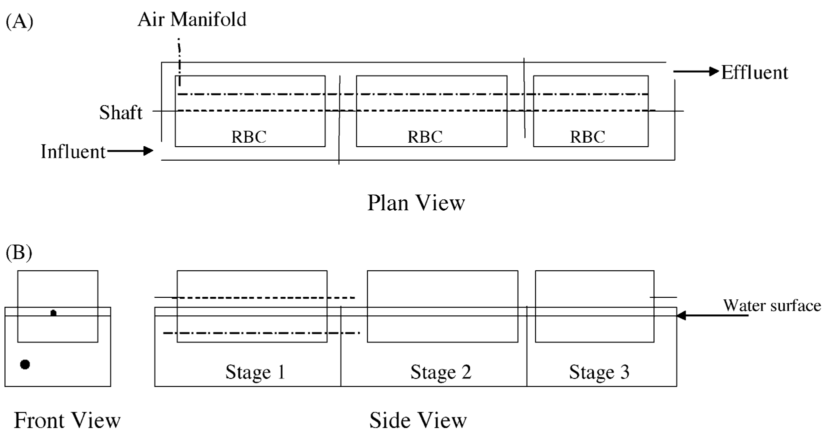

Fig. 2. A schematic diagram depicting the RBC unit configuration and water flow path.

surface area. The RBC was operated at 40% submergence and rotated at approximately 1 rpm (peripheral velocity of 0.39 m/s). The water retention time in the 59 m^3 RBC vessel was approximately 16 min. Pressurized air (the only mechanism used to rotate the RBC) was distributed through a header pipe submerged under one side of the RBC media (Fig. 2B).

At the start of testing, all RBC units had been in continuous operation for more than five years at similar loadings. Water quality within each culture system was also maintained by routine water exchange—after the addition of approximately 227 kg feed, the multi-tube clarifier is emptied, the media sprayed down to remove collected solids and the tank refilled. This equated a freshwater replacement of 4% of the total system volume every 1–3 days, depending on daily feed input, which ranged between approximately 82 and 227 kg. Cumulative feed burden (CFB, kg feed/m^3 of freshwater/day) values were calculated as:

$$\mathrm{CFB} = \frac{F}{V_{\mathrm{FW}}} \tag{4}$$

where F is the daily mass of feed (kg) delivered and V_{FW} is the volume (m^3) of freshwater added per day.

3.2. Sample collection and analysis

Grab-type water samples were collected from the inlet and outlet of each RBC stage at intervals equivalent to the stage retention time and used to characterize the nitrification kinetic performance. Four RBCs units were sampled on two consecutive days following this methodology. Five other RBC units were also evaluated during the study period; however, water samples from these units were collected only from the inlet to the first stage and the outlet of the final stage. Once collected, pH was measured and the samples immediately split into two aliquots. The first aliquot was filtered through a 1.2 μm glass fiber filter, previously rinsed with distilled water and ignited for 30 min at 550 °C. This aliquot was further subdivided into two portions. One portion was immediately placed in a freezer (−20 °C) and used for ammonia, nitrite, and nitrate determination. The remaining portion was acidified (pH < 2) with sulfuric acid and later used to determine the dissolved organic carbon concentration (DOC). The second portion of the original sample collected was not filter but acidified (pH > 2) and used to determine total organic carbon (TOC) concentration. All samples were immediately placed in a freezer following preparation then transported back to our lab for analysis.

TOC and DOC were analyzed using a total organic carbon analyzer (Shimadzu TOC-V, Kyoto, Japan). Ammonia was analyzed using ion chromatography (IC) with a conductivity detector and an IonPac CS12A cation column protected by an IonPac CG12 guard column (Dionex ICS-90, Sunnyvale, CA, USA). Nitrite and nitrate were analyzed with an ion chromatography system using conductivity detection (Dionex, Sunnyvale, CA, USA). Anion separation was carried out on a Dionex IonPac AS14A column protected by an IonPac AG14A guard column. Samples were filtered through a 0.45 μm Supor membrane filter prior to IC analysis (Gelman Sciences, Ann Arbor, MI, USA). Randomly selected water samples were analyzed following colorimetric/spectrophotometer procedures (HACH, Loveland, CO) to validate IC results and agreed within ±3–5%.

Water samples for dissolved carbon dioxide and alkalinity were obtained by submerging a glass aspirator bottle below the water surface with the mouth of the bottle turned down and then inverted to allow water to fill the bottle. Collected samples were immediately analyzed following standard methods procedures 2320 and 4500 for titrimetric determination of free carbon dioxide and alkalinity, respectively (APHA, 1998).

3.3. Data analysis

First-order rate constants, K_i, were determined and used to predict ammonia removal performance using series of algorithms proposed by Watten and Sibrell (2005).

3.3.1. Model development

Nitrification is treated as a two-step consecutive chemical reaction where the removal rate is influenced by the active biomass concentration, reactor volume, and the reactor hydrodynamic characteristics, i.e. plug flow verses mixed flow. Individual RBC stages are treated as complete stirred tank reactors for which

Watten and Sibrell (2005) provided mixed-flow conversion models:

$$[\mathrm{TAN}]_{\mathrm{out}} = [\mathrm{TAN}]_{\mathrm{in}}\left(\frac{1}{1+K_1 t}\right) \tag{5}$$

$$[\mathrm{NO_2-N}]_{\mathrm{out}} = [\mathrm{TAN}]_{\mathrm{in}}\left(\frac{K_1 t}{(1+K_1 t)(1+K_2 t)}\right) + [\mathrm{NO_2-N}]_{\mathrm{in}}\left(\frac{1}{(1+K_2 t)}\right) \tag{6}$$

$$[\mathrm{NO_3-N}]_{\mathrm{out}} = [\mathrm{TAN}]_{\mathrm{in}}\left(\frac{K_1 K_2 t^2}{(1+K_1 t)(1+K_2 t)}\right) + [\mathrm{NO_2-N}]_{\mathrm{in}}\left(1-\frac{1}{(1+K_2 t)}\right) + [\mathrm{NO_3-N}]_{\mathrm{in}} \tag{7}$$

Here, K_1 and K_2 are the first-order rate constants (1/time) for ammonia and nitrite, respectively, and t is the reactor hydraulic retention time (time).

3.3.2. Model calibration

Using changes in [TAN], K_1 values were determined using the following equation for mixed-flow conversion models (Watten and Sibrell, 2005):

$$K1 = \frac{\left[\left(\frac{1}{[\mathrm{TAN}]_{\mathrm{out}}/[\mathrm{TAN}]_{\mathrm{in}}}\right) - 1\right]}{t} \tag{8}$$

K_2 is then calculated by trial and error of Eq. (6) and a corresponding K_1 from Eq. (8). The SOLVER function in EXCEL (Microsoft® 2002) was used to conduct this analysis. Following this procedure, stage specific K_1 and K_2 values were determined using $[\mathrm{TAN}]_{\mathrm{in}}$, $[\mathrm{TAN}]_{\mathrm{out}}$, $[\mathrm{NO_2-N}]_{\mathrm{in}}$, $[\mathrm{NO_2-N}]_{\mathrm{out}}$, and t measurements values from the individual RBC stage measurements from the four RBC units sampled for kinetic modeling.

3.3.3. Model verification

Differences between RBC stage biofilm characteristics occur as the microbial flora acclimates to the specific inlet water quality of a particular stage (Metcalf and Eddy Inc., 1991; Grady et al., 1999). Thus, predicted RBC $[\mathrm{TAN}]_{\mathrm{out}}$ values were determined by sequentially solving Eq. (5) for each stage using the average stage specific K_1 and t values rather than the average K_1 for all three stages. Here, the measured $[\mathrm{TAN}]_{\mathrm{in}}$ for a stage 1 was used to calculate the stage 1 $[\mathrm{TAN}]_{\mathrm{out}}$, which then served as the stage 2 $[\mathrm{TAN}]_{\mathrm{in}}$ to calculate $[\mathrm{TAN}]_{\mathrm{out}}$ for stage 2. Finally, the calculated stage 2 $[\mathrm{TAN}]_{\mathrm{out}}$ value served as the stage 3 $[\mathrm{TAN}]_{\mathrm{in}}$, which was used to determine the stage 3 $[\mathrm{TAN}]_{\mathrm{out}}$. This modeling was conducted with $[\mathrm{TAN}]_{\mathrm{in}}$ measured for those RBC units ($n = 5$) where only inlet and outlet samples were collected. The predicted outlet TAN concentrations were then compared to the measured TAN concentrations for that same RBC unit. Model accuracy was described based on the mean error calculated as Error (mg/L) = abs(predicted RBC $[\mathrm{TAN}]_{\mathrm{out}}$ – measured RBC $[\mathrm{TAN}]_{\mathrm{out}}$) and $\mathrm{Error}_{\mathrm{relative}}$ (%) = Error/predicted value.

Performance characteristics and performance curves were analyzed graphically using Sigma Plot v8 (SPSS Inc., Chicago, IL) curve fitting procedures. Descriptive statistics and mean comparisons were conducted using statistical procedures available in SAS Version 8.2 (SAS Institute, Cary, NC). Influent water quality parameter values were first analyzed using a two-factor (CFB and time) ANOVA. Time was not identified as significant, eliminated from the model, and the data reanalyzed with one-way (ANOVA). Significant differences were determined at the 0.05 alpha level (α).

4. Results and discussion

Each of the RBC units was operated at a hydraulic loading rate of approximately 407 m^3/m^2 surface area per day (10 GPD/ft^2). As a result, changes in mass loading rates reflect changes in influent substrate concentration rather than changes in flow. Table 1 presents the influent water quality conditions under which the RBCs functioned. Single factor analysis revealed that water quality parameters did not differ statistically between CFB values.

4.1. Ammonia oxidation performance

Ammonia removal efficiency was relatively linear as influent TAN concentration approached 3.5 mg/L (equating to mass loading of approximately 1.45 g/m^2/day) before becoming asymptotic at approximately a 40% removal efficiency as described by the solid trend line (Fig. 3A) while the mass ammonia removed

Table 1
Mean ± standard deviation water quality parameter values of the fish culture water entering the RBC units ($n = 3$ per group) installed in tilapia recirculating aquaculture systems

Parameter (mg/L)	Cumulative feed burden (kg/m^3)		
	5.5	6.0	7.8
Temperature (°C)	28.41 ± 0.9	28.35 ± 1	27.28 ± 1.4
TAN	2.74 ± 1.1	3.00 ± 0.3	3.60 ± 1
NO_2–N	0.53 ± 0.1	0.48 ± 0.1	0.52 ± 0.1
NO_3–N	69.75 ± 13.9	65.0 ± 6.7	69.62 ± 13.7
TOC	15.85 ± 5.0	17.71 ± 5.7	14.50 ± 4.5
DOC	11.61 ± 2.8	12.50 ± 3.8	9.49 ± 2.9
CO_2	46.34 ± 11.5	48.40 ± 9.7	51.66 ± 4.7
pH	6.95 ± 0.1	6.93 ± 0.1	6.86 ± 0.1
Alkalinity	151 ± 32	157 ± 37	149 ± 24

Cumulative feed burden (CFB) calculated as kg of feed delivered per m^3 of freshwater added to the system daily. One-way analysis of variance did not detect any significant differences between CFB groups.

continued to increase. The RBCs achieved an averaged areal ammonia removal rate of 0.43 ± 0.16 g/(m^2 day), increasing linearly ($r^2 = 0.80$, slope and y intercept coefficients of 0.65 and −0.40, respectively) with mass loading (Fig. 3B). The areal ammonia removal rates observed here compare favorably to rates reported for other aquaculture-based RBC systems (Fig. 4) as well as a commercial-scale microbead filter, ranging between 0.45 and 0.6 g/m^2/day (Greiner and Timmons, 1998) and a commercial-scale trickling filter with ammonia removals between 0.24 and 0.55 g/m^2/day (Kamstra et al., 1998).

4.2. Hydraulic and organic loading

The hydraulic loading under which these RBC units operate was twice the highest manufacturer rating presented in Fig. 5 and approximately 25% higher than the maximum design flow rate of 300 m^3/m^2/day recommended by Hochheimer and Wheaton (1998). Rogers and Klemetson (1985) reported that ammonia removal efficiency declined as the hydraulic loading of a RBC increased. Easter (1992), while modeling RBC performance, demonstrated that increasing the detention time improved the single-pass ammonia oxidation

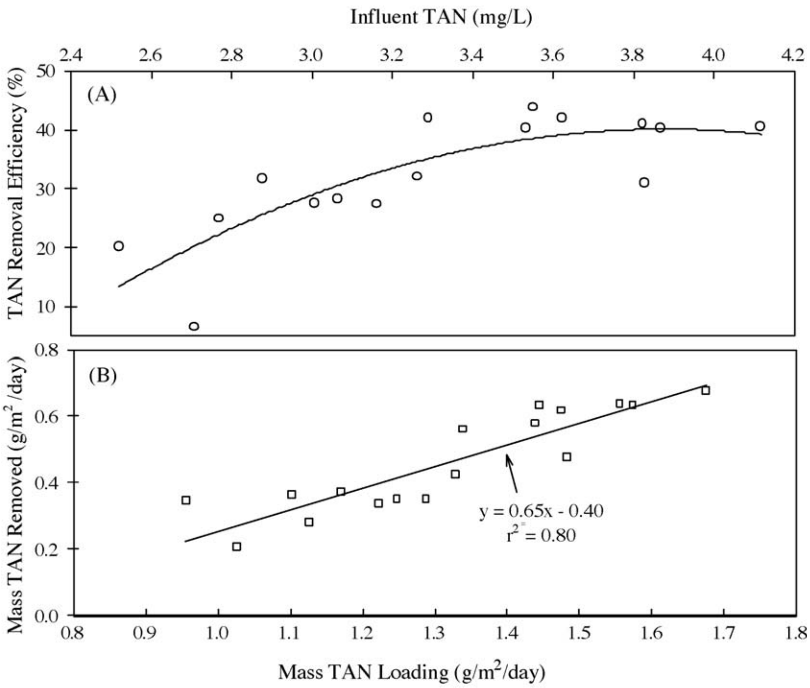

Fig. 3. RBC performance presented as a function of mass loading and influent concentration in both plots. The trend line provided in plot (A) used to describe the observed asymptotic nature of ammonia removal efficiency as it approached 40%. Ammonia mass removal is depicted in plot (B).

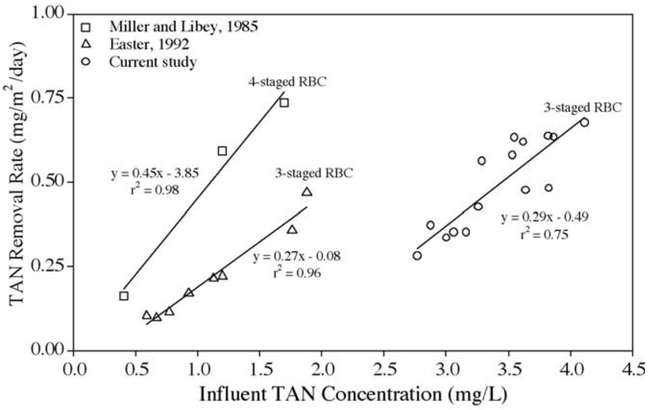

Fig. 4. Comparison of the RBC areal ammonia removal rates in different aquaculture environments. Miller and Libey (1985) and Easter (1992) studied 0.66 m × 0.66 m and 1.8 m diameter RBC units, respectively.

efficiency. However, the realized mass removal of ammonia at the lower flow rate remained smaller than the mass of ammonia removed with a higher flow rate and reduced efficiency, which was similarly reported by Drapcho and Brune (1984).

During this evaluation, organic carbon constituents were not readily removed by the RBC. DOC concentrations were reduced an average 6.5% at ambient concentrations ranging between 4 and 14 mg/L (Fig. 6). The influent carbon to nitrogen ratio (expressed here as C:TAN) strongly influenced the ammonia removal performance (Fig. 7). It was observed that the TAN removal efficiency decreased by approximately 55% when the C:TAN ratio exceeded 3.5. This trend was also observed by Zhu and Chen (2001) studying the effect of sucrose on nitrification in series reactors treating a simulated effluent stream. Zhu and Chen (2001) reported that at C/N (where carbon, C, was in the form of sucrose and nitrogen, N, as ammonia carbonate) ratios of 1 and greater, the ammonia removal efficiency decreased by 70% as compared to ammonia removal at C/N ratios = 0. Ling and Chen (2005) confirmed these previous findings while studying the impact of COD/N at ratios from 0 to 3, which approached the levels under which the RBC units studied here operated.

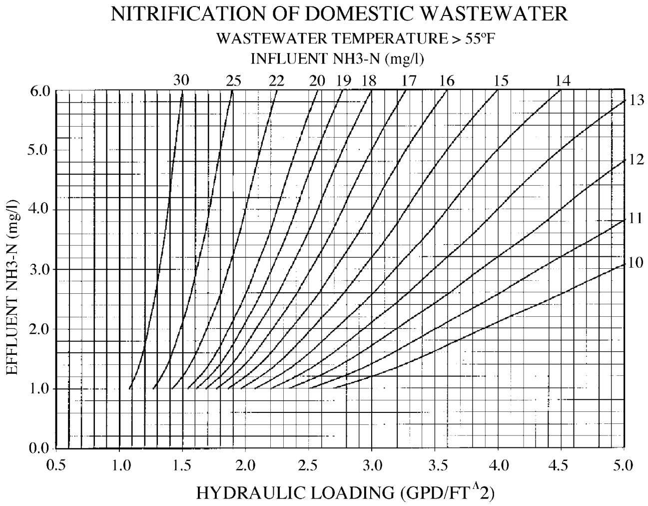

Fig. 5. Standard design curve used to size RBC systems for treating domestic wastewater. Data sheet courtesy of Envirex Inc., US Filter (Waukesha, WI).

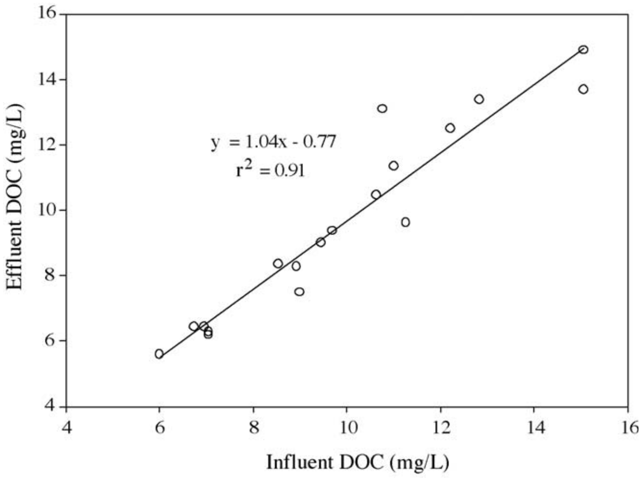

Fig. 6. DOC removal performance achieved by the RBC system treating recirculating fish culture water. The r^2 value near 1 indicates a low removal efficiency, average 6.5%.

The reduction in nitrification was likely a result of heterotrophic bacteria competition for surface area on the RBC media. The maximum growth rate for heterotrophic bacteria is nearly five times greater than that for nitrifying bacteria (Hagopian and Riley, 1998; Zhu and Chen, 2001). This difference in growth rates allows heterotrophic bacteria to out compete the nitrifying bacteria for space and displace them within the biofilter (Ohashi et al., 1995; Okabe et al., 1995; Gupta and Gupta, 2001), thus reducing nitrifying capacity (Bovendeur et al., 1990; Hagopian and Riley, 1998).

CFB in the systems evaluated ranged from 5.5 to 7.8 kg feed/m^3 of replacement water, over which no correlations to performance were observed. Additionally, organic constituents are generated during the bacterial decomposition of the fish feces, uneaten feed as well as direct excretion by the fish (Chen et al., 1994). In addition to negatively affecting nitrification, organic compounds can negatively affect fish feeding and health (Hirayama et al., 1988). Ozonation has been successfully employed to control organic accumulation in recirculating systems, which has improved fish health and led to improvements in nitrification performance (Krumins et al., 2001).

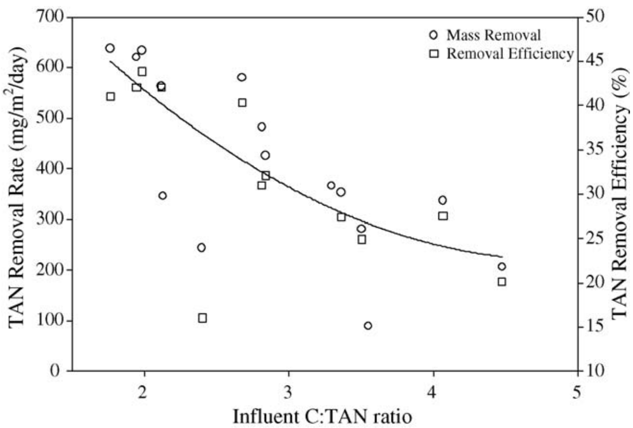

Fig. 7. The impact of influent carbon to TAN ratio on ammonia removal. Solid line demonstrates the observed trend.

The improvements were attributed to the reduction in organic concentrations, effectively reducing the substrate that heterotrophic bacteria utilize.

4.3. Nitrification kinetic modeling

The average stage specific first-order conversion rate constants for ammonia (K_1) and nitrite (K_2) are presented in Fig. 8. Both conversion rate constants were higher across stage 1 (highest K_2) and stage 3 (highest K_1) than across stage 2. This observed variation in rate constants was also reported by Watten et al. (1993), studying nitrification in three plastic bead fluidized bed filters operating at influent ammonia–nitrogen concentrations between 0.2 and 1.5 mg/L at 14.5 °C. K_1 and K_2/K_1 ratio ranged from 12 to 20 h^{-1} and 1 to 3 h^{-1}, respectively.

The plot in Fig. 9 (the solids line denotes 100% accuracy) depicts the relative accuracy of the mixed-flow model presented by Watten and Sibrell (2005) using estimated K_1 values for each RBC stage. The absolute error associated with using the mixed model to determine $[TAN]_{out}$ was 0.22 mg/L, with a corresponding relative error of 9.6%.

4.4. Carbon dioxide removal

Carbon dioxide removal averaged 39% and was not related to influent concentration (Fig. 10). This rate was comparable to a cascade aeration column studied by Summerfelt et al. (2003) where CO_2 removal efficiencies ranged from 32–37% at air:water volume ratios between 5.1:1 and 9.9:1. With respect to air:water volume ratio, the RBC units studied here were rotated by air diffused at rate of 489 m^3/h along one side of the RBC disc. This represented an air:water volume ratio of to 2.2:1. At similar air:water volume ratios, the cascade aeration column removed less than 25% of the influent CO_2 (Summerfelt et al., 2003). In practice, the true air:water volume ratio for these RBC units was unknown as it was also affect by the culture room air ventilation system. Additional CO_2 desportion likely occurred from the liquid film surrounding the biofilm to the air during atmospheric exposure (Poalini, 1986). Finally, turbulence created as the RBC media passed through water surface would have also increased the water surface area and provided more opportunity for carbon dioxide and oxygen transfer (Woods et al., 1996).

4.5. Comparisons to other filter types

The ammonia removal performance of RBC filter systems have compared favorably to other filter types used in aquaculture. Miller and Libey (1985) demonstrated that the RBC provided better removal efficiencies than a packed tower or fluidized bed reactor, when treating the same recirculating fish

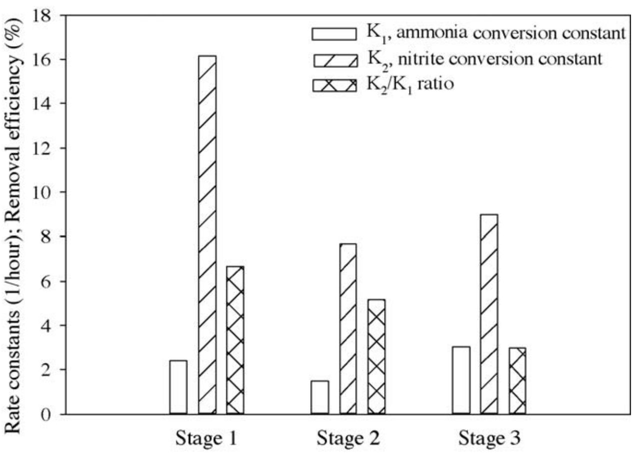

Fig. 8. Average ($n = 6$) first-order conversion rate constants for nitrification across a RBC system operating within a tilapia RAS. Rate constants were calculated following the mixed flow nitrification procedure presented by Watten and Sibrell (2005). Media specific surface area = 175 m^2/m^3, operating temperature 28 °C.

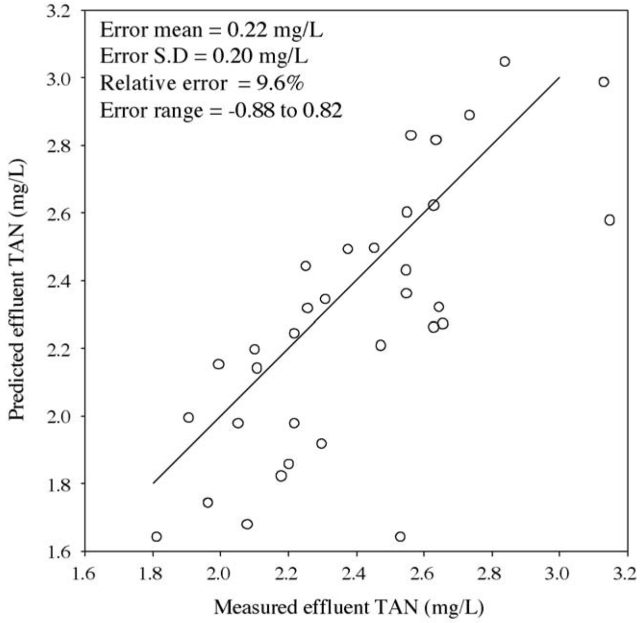

Fig. 9. Accuracy of a first order rate model used to predict TAN concentration in the effluent from the third stage of a RBC (water temperature = 28 °C). Predicted values were calculated following the mixed flow nitrification procedure presented by Watten and Sibrell (2005). The solid line depicts the regression fit if the modeling exactly described the nitrification conversion rate constants.

culture water at comparable hydraulic loadings. The authors reported that RBC NH_4–N removal rates ranged between 0.19 and 0.79 g/(m^2 day) whereas the packed tower removal rate averaged 0.24 g N/(m^2 day). Rogers and Klemetson (1985) used a simulated waste stream to characterize the performance of a submerged bed filter, trickling filter, biodrum, and RBC under various hydraulic loading conditions. For all filters, the ammonia removal rate decreased with increasing hydraulic loading, yet the

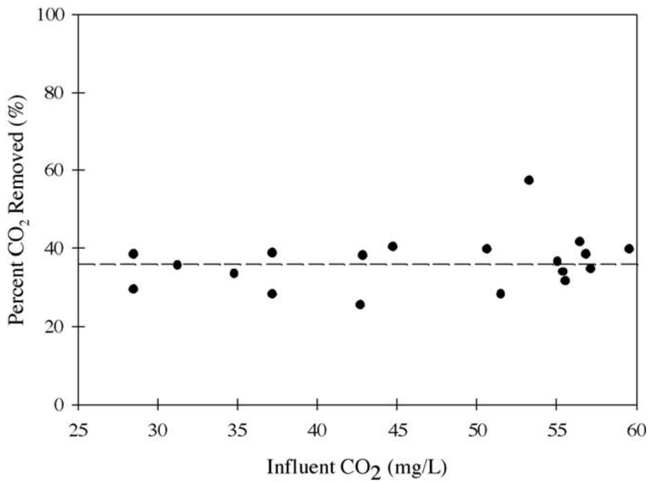

Fig. 10. Dissolved CO_2 removal achieved by an air driven RBC system treating recirculating tilapia culture water. Dashed line represents the average CO_2 removal for a packed tower (Summerfelt et al., 2003).

RBC maintained a removal efficiency of more than 60% over a wider range (up to four-fold increase) of hydraulic loadings. Similarly, Greiner and Timmons (1998) observed that trickling filters and microbead filters could accommodate nearly a three-fold increase in hydraulic loading without experiencing reduced nitrification rates.

Other favorable characteristics of the RBC include low head requirements to move water through the vessel, which reduces operational costs, passive aeration and CO_2 removal, and limited vulnerability to solids clogging (Wheaton et al., 1994b; Timmons et al., 2002; Van Gorder and Jug-Dujakovic, 2004). Each of these could be an issue for other filter types, particularly operation costs associated with fluidizing sand beds or pressurizing bead filter vessels, when compared to the head loss of an RBC vessel. An attribute often overlooked with the RBC has been its contribution to gas conditioning (Kubsad et al., 2004). Woods et al. (1996) demonstrated the influence of RBC gas transfer coefficient (K_La) on RAS oxygenation costs. As a result of the supplemental aeration provided by the RBC, Woods and co-workers reported that lower oxygen injection rates were required to achieve the desired dissolve oxygen levels in the culture tank.

Concerns over mechanical failure have likely prevented broader application of the RBC. In the aquaculture industry, many of the early RBC systems were ‘‘home built’’, which resulted in failures such as media detaching from shafts (Timmons et al., 2002). Once in the vessel, broken media would often plug outlets and prevent water from returning to the culture tanks, or lodge and prevent the shaft from rotating, eventually destroying motors used to rotate the shaft. Early RBC failures in the domestic wastewater industry were associated with media deterioration and shaft breaks under the weight of the accumulating bacterial biomass. The development of improved plastics, stronger shafts, and improved bearings has significantly reduced such failures. In fact, the RBC systems studied here have not experienced any catastrophic failures since initial commissioning in 1989. The only routine maintenance required is to grease bearings and replace as necessary. Additionally, Van Gorder and Jug-Dujakovic (2004) describe RBC units that do not require bearings by including styrofoam disks in the RBC to increase buoyancy; thus eliminating the maintenance requirement with mechanical bearings.

With respect to economic efficiency, little information has been compiled and reported for comparisons between biofilter types treating fish culture water. Timmons et al. (2002) computed that the capital cost of commercial RBC units greatly exceeds that of the fluidized sand bed and microbead filters, bead filters, and is similar to that of trickling filters. However, this analysis did not include operational costs, which could be higher for the fluidized sand filter and can be lower than the trickling or microbead filters, as well, depending upon the lift requirement used for these filters as compared to the RBC. Therefore, a detailed analysis that includes operational costs should be included in addition to a performance analysis before selecting a biological filter.

5. Conclusions

The industrial-scale RBC system in a recirculating tilapia culture system achieved an average removal rate of 0.42 g TAN/(m^2 day). Increases in ammonia concentrations improved removal efficiency up to an ammonia concentration of 3.5 mg/L, beyond which removal efficiency remained about 40%. In contrast, dissolved carbon reduction (measured at DOC) was typically less than 10% per pass and yet ammonia oxidation was negatively impacted by increasing C:TAN ratio. TAN removal efficiency decreased by nearly 50% when the C:TAN ratio reached 4.5. The ammonia oxidation kinetic rate was fairly well described using a first order rate model. With respect to dissolved gas control, the RBC system provided dissolved CO_2 removal equivalent to the cascade aeration columns. Additionally, sufficient oxygenation for nitrification was maintained as the culture water traveled through the treatment vessel.

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